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Improving participation of doubly fed induction generator in frequency regulation in an isolated power system

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ABSTRACT

An increasing penetration of renewable power resources (particularly wind farms) is observed in power systems during the last years. There is a frequency control concern with these kinds of power resources because they do not provide the so-called inertial response. Since the doubly fed induction generator (DFIG) equipped with Variable Speed Wind Turbine (VSWT) is the mostly used type of generator in wind farms, this paper proposes a new control approach allowing the DFIG to participate more efficiently in the power system frequency control. The approach consists of three steps: (1) Estimating the active power mismatch ΔP_0 between the active electrical power and the mechanical power which appears at the first moment after the perturbance at the DFIG, (2) based on ΔP_0 determine the electrical power reference P_{ref} of the active power controller, and (3) appropriate removal of ΔP_0 if the power frequency deviation is above a prescribed value and the automatic generation control (AGC) is activated. The obtained simulation results on a simple 2-bus system and on IEEE 14-bus test system show that the proposed approach has several advantages over existing approaches.

1. Introduction

Frequency is an important parameter which value has to be controlled around the reference value (60 Hz or 50 Hz) for a reliable operation of a power system [1,2]. The mismatch between the generated and the consumed active power is the cause of frequency variation. If the rate of change of the frequency (ROCOF) is important, the under frequency load shedding (UFLS) is activated in order to restore the frequency [3]. However, for economical and reliability reasons the activation of UFLS is undesirable and must to be the last resort. In large interconnected power systems, the ROCOF is generally very low. This is not the case in isolated systems after power system separation [4–9].

If the isolated system has renewable power resources (wind and solar farms), the ROCOF will be more severe. This is because these kinds of resources, in contrast to traditional synchronous generators (SG) equipped with hydraulic or steam turbine do not provide the so-called inertial response. In [10] two approaches are identified for frequency regulation with DFIG: inertial and suboptimal controls. In [11], authors show that there are losses during suboptimal control. The frequency response characterized by the ROCOF and the frequency nadir is analyzed in [12] after the loss of the largest generator in the analyzed power system. In [13], authors show that the replacement of conventional generators by the wind generators will result in increased ROCOF due to the lack of the inertial control. Ref. [14] investigates the contribution of DFIG to system frequency response on an isolated power system consisting of a diesel generator and a DFIG. In [15,16], the role of wind generation in a system's primary frequency control is studied. In [17], the DFIG control system was modified to introduce inertial response.

Inertial response can be defined as the process of the kinetic energy variation of the turbine-generator unit if at that unit there is a mismatch between the mechanical and the active electrical power before the activation of the primary active power reserve. Inertial response plays an important role in limiting the ROCOF, and hence the frequency deviation nadir (maximum frequency deviation) after a perturbance which results in active power deficit.

This paper presents a frequency control problem in an isolated electrical power system which generation consists of traditional SG and DFIG equipped with VSWT. The interest on a DFIG–VSWT unit is based on the fact that it is the mostly used type of units in wind plants due to several economic and technical performances [18–21].

Several approaches have been proposed in order to deal with the frequency control in the presence of wind power generation. Broadly, these approaches can be divided into three categories:

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(1) Limitation of the maximum penetration of the wind power generation: For example, in [22] this limit is fixed to 30%. However, this approach is not the best one as it will lead to the limited use (although available) of renewable sources of energy.
(2) Operation in suboptimal mode [23–26]: In this mode DFIG–VSWT unit operates at power that is lower than the maximum available from the wind power. The major drawback is that some power is lost. The advantage is the presence of some primary power reserve which can be used in the event of active power deficit. The activation of this reserve is performed via pitch angle control. The maximum power which can be used is achieved when DFIG–VSWT unit will operate in optimal (maximum power point tracker) mode.
(3) Use of the kinetic energy stored in the rotating mass of the DFIG–VSWT unit: In this case, normally the unit operates in optimal mode where P_{ref} is equal to the optimal power P_{opt}. The value of P_{opt} is determined by the maximum available power. In case of active power mismatch ΔP_0, the value of P_{ref} is increased according to this value. This creates a mismatch between the mechanical and the active electrical power at the unit that leads to the variation of the stored kinetic energy. Depending on the way the amount of ΔP_0 is determined, one distinguishes two cases.
    (a) Case 1: In this case ΔP_0 is proportional to the ROCOF and/or frequency deviation [14,16]. This is to mimic the behaviour of the SG. A low-pass filter is used to reject measurement noise, since differentiating a signal which contains noise, may destabilize the system. However, as we will see in Section 4 of this paper, this approach has some limitations. Note that when the frequency deviation is used, it is necessary to prevent the contribution of DFIG in steady state (when the frequency deviation remains constant). For this the use of a high-pass filter is proposed in [27].
    (b) Case 2: The value of the ΔP_0 is fixed to a given amount of active power. For example, in [28] this amount is chosen from 5% to 10% of the unit's rated power. In this case a recovery procedure is necessary in order to return to the optimal mode [29].

In this paper, as the best control strategy, we adopt the approach of using the kinetic energy stored in the DFIG–VSWT unit. The value of ΔP_0 has an appropriate amount depending on the proximity of the perturbance to DFIG.

The main contributions of the paper can be summarized as follows:

(1) The distribution of power impacts theory [2] is used to explain the limited contribution to the inertial control of the DFIG–VSWT unit.
(2) A new approach to estimate the appropriate amount of ΔP_0 and its maximum value is proposed. This estimation is performed locally (no communication links are needed) at the DFIG–VSWT unit. Using the estimated amount of ΔP_0, the DFIG–VSWT unit will contribute to compensate only part of the active power mismatch, which appears in the first moment after the perturbation. The remaining mismatch will be compensated by the SG. In this way, the activation of the primary power reserve from the SG will not be delayed.
(3) Recommendations for an effective recovery procedure are also proposed.

The paper consists of four sections. Section 1 gives the introduction. In Section 2, a theoretical analysis to explain the limited contribution of DFIG–VSWT unit to the inertial response is described. The ROCOF in power systems with and without DFIG are compared. Section 3 describes the proposed control approach to improve the power system frequency response after the perturbation. Section 4 presents a detailed discussion of the obtained simulation results and conclusion is given in Section 5.

2. Frequency concern in power system with DFIG

The effect of active power mismatch between the mechanical power deviation, ΔP_i^m and the electrical power deviation, ΔP_i^e on ith electrical machine in power systems is described by the following differential equation [1,2]:

$$\frac{2H_i}{f_n}\frac{df_i}{dt} = \Delta P_i^m - \Delta P_i^e \tag{1}$$

where

H_i is the inertia constant of the ith machine;
f_n is the nominal frequency in Hz (f_n = 60 Hz in North America).

In this section, we will be concerned in the time range of less than one second. In this case, the turbine mechanical power will be almost constant. Thus,

$$\frac{df_i}{dt} = -\frac{f_n}{2H_i}\Delta P_i^e \tag{2}$$

Assume that at a certain moment $t = 0^+$, an active power mismatch $\Delta P_k(0^+)$ between the generation and load appears at node k of the power system. This mismatch will be immediately distributed among the generators in service. The mismatch supplied by ith generator according to [2] is determined as:

$$\Delta P_i(0^+) = \alpha_i \Delta P_k(0^+) \tag{3}$$

where

$\alpha_i = \frac{P_{sik}}{\sum_{j=1}^{n} P_{sjk}}$ and P_{sik} is the synchronizing power coefficient between nodes i and k.

The synchronizing power coefficient depends upon the susceptance B_{ik} and $\cos(\delta_{ik})$. In this case the initial ROCOF is determined by:

$$\frac{df_i}{dt}(0^+) = -\frac{f_n}{2H_i}\alpha_i \Delta P_k(0^+) \tag{4}$$

Eq. (4) shows that during the first periods after the appearance of the active power mismatch, the initial ROCOF of the generators are different. For the sake of simplicity, in this section we will assume that the initial ROCOF of the whole system is determined by the average initial ROCOF $\frac{df_{ave}}{dt}(0^+)$ determined as follows:

$$\frac{df_{ave}}{dt}(0^+) = \frac{\sum_{i=1}^{n}\frac{df_i}{dt}(0^+)}{n} \tag{5}$$

where n is the number of the generators in the power system.

To understand the impact of the presence of the DFIG in the power system on the initial ROCOF, consider a simple power system with only two generators in two different configurations A and B. In each configuration the generators have the same inertia (H1 = H2 = H). The two configurations are analyzed below.

2.1. Both generators are synchronous generators

In this case, according to (4):

$$\frac{df_1}{dt}(0^+) = -\frac{f_n}{2H}\alpha_1 \Delta P_k(0^+) \tag{6}$$

$$\frac{df_2}{dt}(0^+) = -\frac{f_n}{2H}(1-\alpha_1)\Delta P_k(0^+) \tag{7}$$

The average initial ROCOF of the power system according to (5) will be:

$$\frac{df_{ave}}{dt}(0^+) = -\frac{f_n}{4H}\Delta P_k(0^+) \tag{8}$$